Seven Key Principles of Program and Project Success – A Best Practices Survey

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Abstract

The NASA Organization Design Team (ODT) team, consisting of twenty seasoned program managers and systems engineers from a broad spectrum of the aerospace industry, academia, and government, was formed to support the Next Generation Launch Technology Program and the Constellation Systems Program. The purpose of the ODT was to investigate organizational factors that can lead to success or failure of complex government programs, and to identify tools and methods for the design, modeling and analysis of new and more efficient program and project organizations. The ODT conducted a series of workshops featuring invited lectures from seasoned program managers representing 25 different large technical programs spanning 50 years of experience. The result was the identification of seven key principles of program success that can be used to help design and operate future program organizations. This paper presents the success principles and examples of best practices that can significantly improve the design of program, project and line organizations, the assessment of workforce needs and organization performance, and the execution of programs and projects. The presentations from the workshops from which the seven key principles were synthesized are included in the appendices.

Nomenclature

ALS	....	Advanced Launch System
ASTP	....	Advanced Space Transportation Program
CAIB	....	Columbia Accident Investigation Board
CEO	....	Chief Executive Officer
CER	....	Cost Estimating Relationship
CEV	....	Crew Exploration Vehicle
CLV	....	Crew Launch Vehicle
CONOPS	....	Concept of Operations
CTO	....	Chief Technical Officer
CTS	....	Crew Transportation System
DC-XA	....	Delta Clipper Experimental Advanced Vehicle
DoC	....	Department of Commerce
DoD	....	Department of Defense
DSM	....	Dependency Structure Matrix
EELV	....	Evolved Expendable Launch Vehicle
FMEA/CIL	....	Failure Mode and Effects Analysis / Critical Items List
FTE	....	Full Time Equivalent
FY	....	Fiscal Year
GRC	....	Glenn Research Center
HQ	....	Headquarters
IOC	....	Initial Operational Capability
IPPD	....	Integrated Product and Process Development
IDT	....	Integrated Discipline Team
ISS	....	International Space Station
JSC	....	Johnson Space Center
JSF	....	Joint Strike Fighter
KSC	....	Kennedy Space Center
LaRC	....	Langley Research Center
LH2/LOX	....	Liquid Hydrogen/Liquid Oxygen
LMC	....	Lockheed Martin Corporation
MSFC	....	Marshall Space Flight Center
NACA	....	National Advisory Committee for Aeronautics
NASA	....	National Aeronautics and Space Administration
NASP	....	National Aerospace Plane
NGLT	....	Next Generation Launch Technology
NLS	....	National Launch System
NOAA	....	National Oceanic and Atmospheric Administration
NPOESS	....	National Polar-Orbiting Operational Environmental Satellite System
NRO	....	National Reconnaissance Office
NYU	....	New York University
ODT	....	Organization Design Team
OMB	....	Office of Management and Budget
ORD	....	Operational Requirements Document
SAIC	....	Science Applications International Corporation
SBA	....	Simulation Based Acquisition
SDI	....	Strategic Defense Initiative
SE&I	....	Systems Engineering and Integration
SFOC	....	Space Flight Operations Contract
SMC	....	Space and Missiles Systems Center
SPO	....	System Program Office
SSC	....	Stennis Space Center
SSTO	....	Single Stage to Orbit
TPS	....	Thermal Protection System
USAF	....	U.S. Air Force
VSE	....	Vision for Space Exploration
WBS	....	Work Breakdown Structure

Background

In January 2003, the National Aeronautics and Space Administration (NASA) established a new program entitled the "Next Generation Launch Technology (NGLT) Program".[1] The purpose of this program was to invest in the development of new technologies that would significantly reduce costs and improve reliability and safety for access to space. A Systems Analysis Project was created within the NGLT program to systematically evaluate the proposed technologies against conceptual space launch architectures for access to space.[2] Architecture analysis teams were established within this project in order to analyze the effect the investments made in these technologies, if successful, would have on important system-level figures of merit (*i.e.*, safety, cost, reliability, and performance). A series of discipline teams were set up to support the architecture teams with a consistent set of ground rules, assumptions, analytical tools and databases. In addition to the traditional aerospace technical disciplines (aeronautics, structures, propulsion, etc.) an Organization Design Team (ODT) was formed in order to explore the impact that the "human systems" of program, project, and technical line organizations have on the space launch "system of systems". The ODT continued its mission by transitioning to support the Constellation Systems Program of the new Exploration Systems Mission Directorate, following termination of the NGLT program in February 2004.

This technical memorandum documents the results of the first of three tracks of research undertaken by the ODT, namely, research into the lessons learned and best practices established within 25 major aerospace programs of the past 50 years.

Approach

The ODT established four tracks of inquiry in order to fulfull its charter, as follows:

Track 1: Survey veteran program/project managers, system engineers, and academics from current and historical complex technical programs and projects in order to identify organization related best practices and lessons learned.

Track 2: Identify tools, methods and databases that could be used by NASA to design, model, simulate, and assess future program, project, and line organizations. This included an assessment of current academic research to model the human interactions associated with formal organization structure as well as more informal "communities of practice" (i.e., networks of technical staff) which typify NASA's frequent use of small, focused "tiger teams" to conduct short term, high impact studies.

Track 3: Apply the most promising tools and methods identified in Track 2 in a series of pilot studies to assess their usefulness to future NASA programs and projects, with a particular focus on emerging organizations involved in implementing the Vision for Space Exploration (VSE) established by President Bush in February 2004.[4]

Track 4: Capture the knowledge developed in tracks 1-3 into a "toolkit" to enable a broader dissemination and adoption of more rigorous project formulation and organization design best practices across the agency.

Leadership of the ODT was assigned to Langley Research Center, which then recruited a national team of seasoned program managers and system engineers from NASA (Johnson Space Center, Kennedy Space Center, Langley Research Center, Marshall Space Flight Center, and Stennis Space Center); industry (Boeing, Lockheed Martin, Northrop Grumman, SAIC, Hernandez Engineering, and Jacobs-Sverdrup), and academic institutions (National Institute of Aerospace). Please refer to Table I-1 in Appendix I for a complete list of ODT members who contributed to the workshop process described herein.

The ODT conducted eight workshops during 2003–2004, inviting representatives of 25 programs spanning the past 50 years to present their thoughts on organizational effectiveness. Each invited speaker provided his or her program/project title, objectives, description, and the historical or political context. The presenters were also asked to provide a snapshot of the program or project's life cycle portrayed as a top-level master schedule or similar graphical display. Key milestone dates, actual task durations, government

(in-house) workforce levels, and annual or total budget data were also collected. The briefings summarized the challenges each program encountered getting through major decision gates, and, for those programs not restricted by proprietary issues, also presented procurement strategies, details of government or customer insight and oversight methods, and the level of government integration with contractor teams (such as integrated product teams). A summary of the workshops can be found in Appendix I Table I-2. The actual presentations from each workshop may be found in Appendices A through H which are included on a companion CD.

Key large aerospace programs reviewed included Apollo, the Advanced Launch System (ALS) and National Launch System (NLS), the National Aerospace Plane (NASP), the National Polar Orbiting Environmental Satellite System (NPOESS), and the Air Force Evolved Expendable Launch Vehicle (EELV). Smaller and/or commercial launch vehicle projects were presented, such as Space X Falcon, DC-XA, Kistler and a series of "X" projects. Systems-of-systems architectures and systems integration approaches were examined via presentations on the Joint Strike Fighter (JSF) Program and the Virginia Class Submarine Program. Other presentations focused on lean organizations, keeping organizations effective over the long term, probabilistic approaches to failure, precursor detection and analysis, as well as insights from the Colombia Accident Investigation Board (CAIB). The team also identified research efforts that are underway to improve the ability to assess organizational effectiveness and measure organization performance.

Results and Key Findings

Using the workshop presentations and team members' extensive experience, the ODT distilled seven key principles that are critical for a program or project to succeed. Though simple in nature, these seven principles address recurring issues identified in the workshop presentations and in many past reviews and independent audits of large government programs. The seven principles are summarized in Table 1.

Table 1. Seven Key Principles of Program and Project Success.

> 1. *Establish a clear and compelling vision.*
>
> 2. *Secure sustained support "from the top".*
>
> 3. *Exercise strong leadership and management.*
>
> 4. *Facilitate wide open communication.*
>
> 5. *Develop a strong organization.*
>
> 6. *Manage risk.*
>
> 7. *Implement effective systems engineering and integration.*

A summary of the programs/projects reviewed by the ODT is presented in Table 2, along with an evaluation of that program/project against the seven key principles. A cell with a + sign indicates evidence of strong implementation of a key principle was found, while a cell with a - sign indicates evidence of weak implementation of a given principle was found, and a blank cell indicates that evidence of the principle was not discussed by the presenters or uncovered by the ODT.

+	Strong implementation of key principle found
-	Weak implementation of key principle found
	No evidence of key principle found

Table 2. Presence of the Key Principles in the Programs and Projects Reviewed.

Program Organizations	Key Principles of Success (from Table 2)						
	1	2	3	4	5	6	7
Apollo	+	+	+	+	+		+
ALS/NLS		–	+	+			
DC-XA SSTO	–	–		+	+	–	+
EELV			+	+		+	
Have Blue/F-117A	+	+	+	+	+	+	
Joint Strike Fighter		+	+	+		+	+
K-1 Launch Vehicle		–			+		
National Aerospace Plane		–			–	–	
Nova Super Saturn M1			+	+			
NPOESS	+	+			+		+
Space Exploration Initiative (1987-91)	–	–					
Space Flight Operations Contract					–		
Space X Falcon	+	+	+		+		
Space Shuttle		–		–	–	–	
Virginia Class Nuclear Submarine		+	+	+	+		+
X-33	–	–		+		–	
X-34							
X-37							
X-38		–		+	+	+	+

Each of these principles and the references which support them are explained in more detail in the sections that follow.

Principle 1: Establish a Clear and Compelling Vision.

Creating a clearly defined vision of the future that serves to inspire and motivate the workforce is an important first step in paving the road toward project success. Top organization leaders must clarify the focus of the program goals and mission, and clearly enunciate their vision of the future to the program team. A vision statement should articulate the overreaching, long-term goals of the enterprise. It is a look beyond the present to see what could be. A vision statement should assert what the organization can be at its best. It may include a definition of what is unique about the enterprise. An effective vision statement should be vivid – something one can describe – so that people may picture it in their minds and then make the connection to how their individual contributions can support realization of the vision. The statement itself should be concise, motivating, and memorable.

Early in its history, NASA was provided a clear vision by President John F. Kennedy to "land a man on the moon and return him safely to Earth." NASA successfully implemented the Mercury, Gemini, and Apollo programs to achieve the national vision he expressed. Dr. Aaron Cohen, former Director of the Johnson Space Center, noted that during the Apollo era, "President Kennedy's vision was fully complemented with support from Congress and the public, and the funding for the project was supported for more than a decade."[5]

The unique circumstances at the time made it possible for President Kennedy to receive Congressional and popular support for Werner Von Braun's ambitious plan, to land an American on the Moon before the end

Figure 1. President John F. Kennedy

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of the decade of the 1960s.[6] The Apollo program required billions of dollars (~$140 B in 2004 dollars), millions of hours, and thousands of men and women, yet, the entire effort was driven by a simple goal: land a man on the moon and return him safely to earth by the end of the decade. In the eight years following the first day the idea was announced, until Neil Armstrong's first step on the lunar surface – there remained little doubt among NASA and industry personnel about what every meeting, every proposal, every budget discussion, or every decision was ultimately intended to accomplish. For almost a decade, President Kennedy's words served as the guiding spirit, pointing the direction for everyone working in the space program.

The Apollo Program was not the only program example evidencing the importance of establishing a vision. Several other successful programs were based on a clear vision and mission. One good example was the F-117A and, in particular, its predecessor HAVE BLUE, which was a prototype USAF Stealth Fighter designed, built and flight-tested for 2½ years during the 1970s. Sherman Mullin, retired president of Lockheed Martin Corporation (LMC) Skunk Works, provided an overview of the HAVE BLUE Program, and stated that HAVE BLUE was successful, in large part, due to a total buy-in of the vision by both the developer (LMC) and the customer (USAF).[11]

The NPOESS Program is another example. This program benefited from a clearly defined vision.[12] Despite the fact that NPOESS is a tri-agency effort (Department of Commerce, Department of Defense, and NASA), with all the political difficulties that this might have entailed, the NPOESS has been successful in combining environmental satellite activities from each organization. The vision has allowed the NPOESS member agencies to put the broader system needs above their own parochial needs to the benefit of all.

Several additional workshop presentations indicated that a clear vision and mission are also important to less complex programs, and correspondingly, smaller organizations. According to Gwynne Shotwell of

Figure 2. SpaceX Falcon V Rocket.

Space Exploration Technologies Corporation (SpaceX), "SpaceX will be demonstrating low cost access to earth orbit primarily because the owner, financier, and chief executive, Mr. Elon Musk, has set a clear vision and established a small team of bright experienced aerospace engineers.[13] Although drawing upon a rich history of prior launch vehicle and engine programs, SpaceX is privately developing the Falcon I and Falcon V rocket family from the ground up. This private development will include the main and upper stage engines, the main engine turbo-pump, the cryogenic tank structure and the guidance system."

On the other hand, a *lack* of vision can be disastrous. While the highly successful lunar missions were being performed, President Richard Nixon rejected a vision for a post-Apollo era that involved full development of low Earth orbit, permanent outposts on the Moon, and initial journeys to Mars, as far too costly. Nixon had no established vision for space exploration, and none was successfully established in the interim until promulgation of the current VSE. There had been several subsequent attempts during the 1970s, '80s, and '90s to establish a clear vision for the space program, but none of these have proven to be successful. For example in 1986, the National Commission on Space proposed "a pioneering mission for 21st-century America: To lead the exploration and development of the space frontier, advance science, technology, and enterprise, and build institutions and systems that would make accessible vast new resources and support human settlements beyond Earth orbit, from the highlands of the Moon to the plains of Mars."[7] Despite some initial enthusiasm for this vision, support soon faded.

In 1989, on the 20th anniversary of the first lunar landing, President George H. W. Bush again proposed a Space Exploration Initiative, calling for "a sustained program of manned exploration of the solar system"[8], but once again follow-up support failed to materialize due to competing budget priorities and a lack of buy-in by the Congress. NASA efforts on the International Space Station were in the early stages of development, and the Station was viewed as a higher priority project needed to solve the human health and risk challenges associated with human space flight beyond low Earth orbit. The lack of a long-term consensus

vision caused near-term goals of the shuttle and the ISS to take precedence, and the Initiative languished for lack of funding support.

Space advocates have been consistent in their call for sending humans beyond low Earth orbit as the appropriate objective of U.S. space activities. Review committees as diverse as the 1990 Advisory Committee on the Future of the U.S. Space Program (chaired by Norman Augustine), and the 2001 International Space Station Management and Cost Evaluation Task Force have suggested that the primary justification for a space station is to conduct the research required to plan missions to Mars or other distant destinations. The Augustine Committee noted, "It seems that most Americans do support a viable space program for the nation – but no two individuals seem able to agree upon what that space program should be."[10]

In several other NASA programs it was not clear if a well defined vision was ever established. These programs included the DC-XA, X-33, National Aerospace Plane (NASP), ALS/NLS (Advanced/National Launch System), and the Space Launch Initiative. Although it is true that these programs developed a range of exciting technologies – including breakthrough approaches such as hypersonic propulsion – these programs essentially failed in their primary goal of bringing into being a next generation space launch system to replace the shuttle. A reason for each of these failures would appear to be the lack of a clear vision and mission. As pointed out in the DC-XA briefing to the ODT by Dan Dumbacher, NASA DC-XA Program Manager, "The Delta Clipper Experimental Advanced Vehicle (DC-XA) was a flight test vehicle that was designed to significantly reduce the cost of access to space, but, in the long run, NASA inherited this project, the SSTO [single stage to orbit] technology and the SSTO vision from the U.S. Air Force."[14] This refocusing of the program on SSTO performance and reduced ownership costs was a major contributor to the X-33 program cancellation in 2001.

Ultimately, this lack of a compelling, guiding vision of the future has had disastrous consequences for the U.S. space program. In 2003, the Columbia Accident Investigation Board (CAIB) published its findings relating to both the physical *and organizational* causes of the Space Shuttle Columbia accident. The CAIB's statement on organizational contributing factors, excerpted in Figure 3, summarizes the importance of vision to program and organization success. The Board noted the lack, over the past three decades, of any national mandate providing NASA a compelling mission requiring human presence in space. The Board attributed NASA's failure to receive budgetary support adequate for its ambitions as consistent with this lack of national vision.[9] The result, as noted throughout Part Two of the CAIB Report Volume I, was an organization straining to do "too much with too little." The second reality, flowing from the lack of a clearly defined long-term space mission, was the lack of sustained government commitment over the past decade to improved U.S. access to space via development of a second-generation space transportation system. Without a compelling reason to do so, successive Administrations and Congresses have not been willing to commit the billions of dollars required to develop such a vehicle.

> *Organization Causes of the STS-107 Failure:*
> *The organization causes of this accident are rooted in the Space Shuttle Program's history and culture, including the original compromises that were required to gain approval for the shuttle program, subsequent years of resource constraints, fluctuating priorities, schedule pressures, mischaracterization of the Shuttle as operational rather than developmental, and lack of an agreed national vision for human spaceflight.*

Figure 3. Columbia Accident Investigation Board's finding Regarding Lack of Vision (underline emphasis added).

In order to respond this overarching CAIB finding, on January 14, 2004 President George W. Bush delivered a speech at NASA Headquarters in which he laid out a compelling future vision of human exploration of the solar system.[4]   After receiving this call to action, NASA immediately reorganized its Headquarters "codes" into "mission directorates" to increase agency focus on this future.   The centerpiece of this realignment was the creation of an Exploration Systems Mission Directorate (ESMD), which was chartered with the task of identifying the requirements and developing the new systems that will be required to accomplish the missions and implement the vision.

In the two years since this Vision for Space Exploration was promulgated, it has served to galvanize and refocus NASA and industry on the future. As of early 2006, NASA has moved aggressively with a three pronged strategy to implement VSE. This strategy includes:

- Return the Space Shuttle safely to flight and use it solely to complete construction of the International Space Station (ISS).

Figure 4. President Bush Establishing the Vision for Space Exploration in January 2004.

- Retire the Shuttle no later than the end of calendar 2010 to free up a budget "wedge" in excess of $4B annually for use in developing future exploration systems, such as a new heavy lift Cargo Launch Vehicle, Earth Departure Stage, and Lunar Surface Access Module for returning humans to the lunar surface.
- Initiate immediate development of a new Crew Transportation System (CTS). This CTS will feature two new systems, a Crew Exploration Vehicle (CEV) and a Crew Launch Vehicle (CLV).

Only time will tell how successful the VSE will be in pulling NASA, industry and the nation toward the future.

Principle 2: Secure Sustained Support "from the Top"

The second key principle for program success is to sustain support "from the top." Sustaining support for large programs requires organizations to develop and maintain program protectors, including outside of the organization at the highest levels (*e.g.*, Congress, the White House, CEOs, and the like). For a NASA program, the management team must develop the overall program plan, the program must be advocated and "sold" to Congress, the Office of Management and Budget, and other government agencies, and funding must be obtained. The manager must develop effective working relationships with key stakeholders at NASA HQ to keep the program sold, and at NASA field centers to maintain enthusiastic internal support t keep the program staffed with the best available talent. Finally, the manager must stabilize the program from distractions and continual re-planning, and protect the program from outside interference.

Protectors are applicable to any size organization or program, and for very large organizations, this could mean developing or maintaining contacts as high as the White House. According to Sherman Mullin the internal protector function for the HAVE BLUE project was performed by the home division CEO.[11] Special financing was set up to protect the secrecy of the special project for which the "Skunk Works" is famous. This top cover allowed the project to be autonomous and also prevented other interests at LMC from interfering with the work in progress.
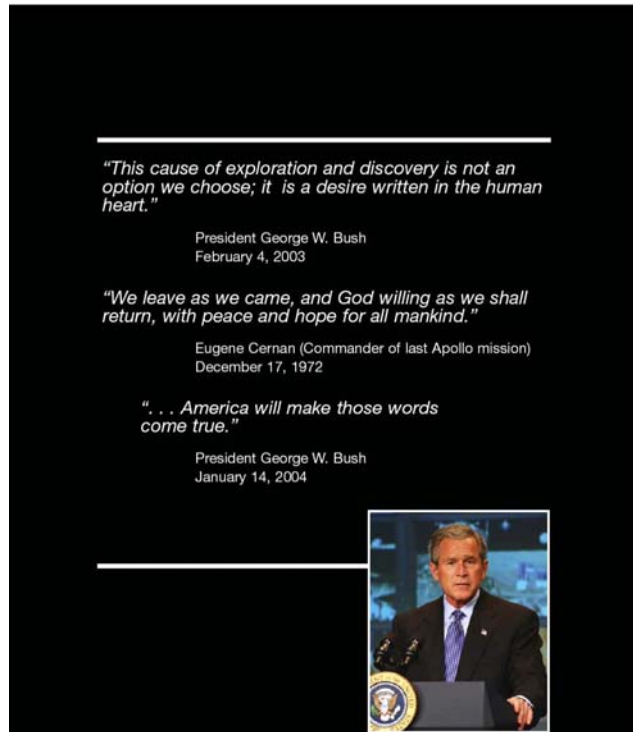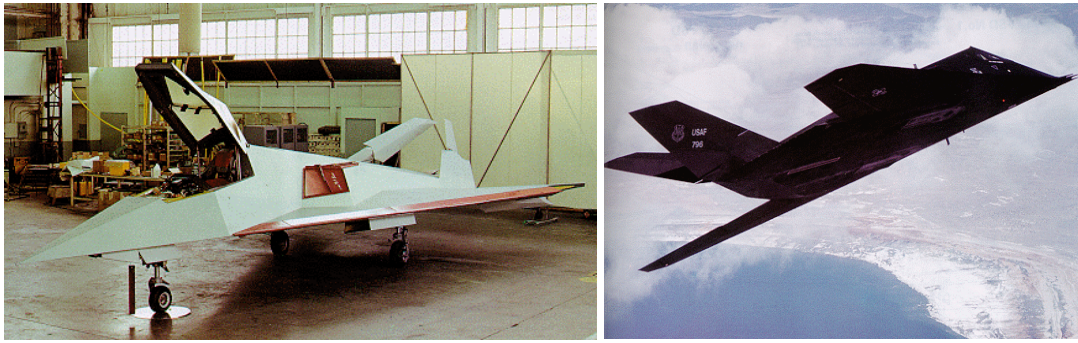
Figure 5. The HAVE BLUE Prototype (left) and the F-117A Stealth Fighter (right).

Examples of successful programs that spanned more than one administration were Apollo, JSF, Virginia Class Submarine, and the F-117A. According to Aaron Cohen, Apollo program "protectors" included Presidents Kennedy and Johnson, NASA Administrator James Webb, and certain high-ranking Senators and Congressman.[5] Apollo did not survive President Nixon, clearly demonstrating the consequences to a major program once top cover protection is lost. The F-117A program also spanned more than one administration, and its protectors included Senators, Staff, senior DoD officials, the USAF, and the LMC CEO.[11] According to Paul Wiedenhaefer, Dr. Paul G. Kaminski, Undersecretary of Defense for Acquisition and Technology, served as JSF's "godfather" in the early days of the program, enabling the program to bypass many established DoD weapons system acquisition practices and thereby setting in motion current acquisition reform practices.[26]

The lack of "protectors" has caused many programs to fail or to be cancelled. The X-38 project that could not survive changes to the project requirements due to lack of a top level protector.[15] Also, both the ALS and NLS programs suffered from a lack of protectors. These programs had their beginnings in President Reagan's Space Defense Initiative (SDI), which called for a very large booster. However, when President Bill Clinton took office, it was determined that the SDI would be de-emphasized and the heavy lift requirement was eliminated. This led to the cancellation of the program despite five years of intense effort by the major aerospace companies.[16]

Principle 3: Exercise Strong Leadership and Management.

Exercising strong leadership is the third principle of success. It requires the leader to:
- Identify and develop other leaders and technical staff within the organization,
- Define clear lines of authority and demand accountability,
- Implement sound project management practices, and
- Demonstrate uncompromising ethical standards.

(a) Develop key leaders and technical staff. The first step in building an organization is to assemble a staff with the experience and expertise needed to meet the goals and objectives of the program. As Dr. Von Braun, a key leader of the Apollo Program often emphasized, these individuals should have capabilities in their field of expertise, far greater than the program leader(s).[17] In short, hire people smarter than you and give them the responsibility and resources needed to accomplish the task.

Aaron Cohen provided the following insight into the Apollo management team: "The management structure for the Apollo program was successful due in large part to very strong leadership in Washington (Dr. George Mueller), strong center directors at MSFC (Dr. Werner Von Braun), JSC (Dr. Robert Gilruth), and KSC (Dr. Kurt Debus). There were also very strong program managers at HQ (Gen. Sam Phillips), MSFC (Dr. Everhardt Rees), KSC (Dr. Rocco Petrone), and JSC (Mr. George Low). Once the basic decisions such as lunar orbital rendezvous (LOR) were made, interfaces between the launch vehicle, spacecraft, and the launch complex became very clear and unambiguous. The integration of the Apollo Program was per-

formed out of Headquarters with the support of General Electric, Bellcom, and later Boeing. MSFC and its contractors performed integration of the various stages of the launch vehicle; and the integration of the command service module/lunar module was performed by JSC and its contractors."[5]

It is also imperative that the key leaders be selected in the formative stages who will then be asked to perform key roles over the life of the program. Dan Dumbacher reported a key lesson learned from the DC-XA program. "Those who made decisions in the contract evaluation and negotiation phases must live with their decisions; those who negotiate should also manage the project over the life of the project, if at all possible. This will ensure that the leader(s) will participate in the formative stages of the 'Program' and will basically 'buy into it.' "[14]

(b) Define clear lines of authority and accountability. The historical experiences have shown that, in successful programs, the responsibility and decision-making authority are allocated down to the lowest level possible, consistent with the individual's capabilities, but with the leader maintaining ultimate accountability. The objective is to clearly define each team member's responsibilities and deliverables within the organization, then provide them with the opportunity to succeed or fail in executing those responsibilities. This makes the organization more agile in making decisions and executing technical tasks and frees the senior managers to focus on the program's major issues and problems. Leadership is all about showing the way and working with people along the way. Effective leaders realize that everyone has a unique personality and needs to be dealt with respectfully and on a one-to-one basis. Although the importance of "open communication" is addressed as a separate subject later in this report, it is also emphasized here because good communication is a key factor in the successful management of any program. It all starts with the communication of a clear and credible set of program objectives to everyone on the team.

An important aspect of effective leadership is the establishment of the responsibilities and authorities of each organization on the team. Strong leadership is required on both sides of the government-industry "aisle". The F-117A is a good example of a "hard charging company program manager" combined with a "competent, decisive military program manager."[11] Skunk Works program managers were typically demanding and decisive with total responsibility and authority. The program managers also had the ability to control team compensation –which may not necessarily have been in accordance with company policies – allowing for better team building and team excellence.
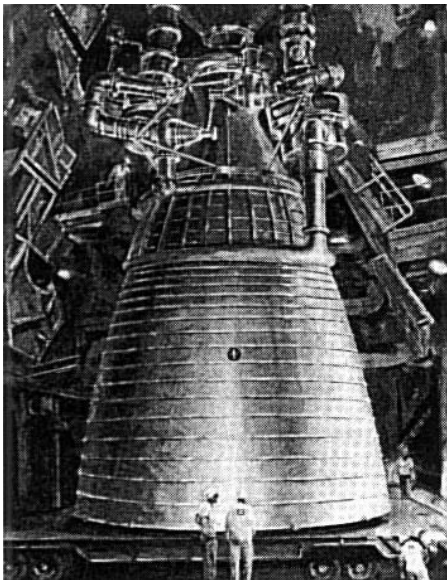

Figure 6. The M-1 Booster Engine.

Mr. Walter Dankhoff, the M-1 booster engine project manager, provided another example of the strong leadership that existed in the early years of NASA. The M-1 was to be a colossal engine designed for the first stage of the then-proposed massive Nova launcher. The M-1 was much larger than the F-1 engines used to power the Saturn V booster. "From the beginning, the government and industry project managers agreed that the M-1 program should be addressed as one team, in all respects. In this way the rocket engineering technical expertise of NASA Lewis Research Center (later renamed the Glenn Research Center) was effectively utilized, along with the Aerojet engineers, in addressing the many challenges involved in developing a very large liquid hydrogen/liquid oxygen (LH_2/LO_2) rocket engine. These two project managers also appreciated and utilized the 'know how' of the NASA MSFC engineers; especially regarding the manufacturing of large rocket engine hardware. A good example of this 'single team' approach was in the conduct of the program reviews. The project held joint monthly program reviews of progress, where the government and industry team openly addressed the current problems. The project leadership also alternated the location of the reviews, one month it was held at Aerojet and the next month it was held at Lewis. Senior technical, financial and contractual personnel from both organizations attended (about 20 total)."[18]

The result was that this team, in a period from 1962-1965, designed, fabricated, and successfully tested, at full-scale, all of the rocket engine components (LO_2 and LH_2 turbo pumps; gas generator; and the thrust chamber). Based on these results, it was concluded that the development, qualification, and operation of a large LH_2/LO_2 rocket engine was feasible.

(c) Implement sound project management. An important activity of an effective program leader is the establishment of close control of schedules and budgets. To allow for this control on a developmental program requires the leader to conduct regularly scheduled program reviews. Over the years NASA has developed a standard program/project life cycle which features a series of program review milestones that serve as "go - no go" gates through which the program must pass on the path to accomplishing the mission. During these reviews all program participants (e.g. government, industry, consultants, and other stakeholders) must be represented. The conduct of these reviews provides an excellent opportunity for implementing Principle 4, "Open Communication." For example, a strong leader fosters open, honest communication, including bringing in bad news, without retribution against the messenger.

John Muratore, X-38 project manager, emphasized that strong project leaders should resist the rush to flight until all technical and safety issues have been resolved.[15] The X-38 management team delayed their flight test program to allow for more aerodynamic analysis to be completed. When the aerodynamic analysis was completed and there was agreement from a independent review team, the project performed the next flight test. Ultimately, the project had two perfect flights of the vehicle.

Figure 7. The X-38 drops from the B52 pylon.

Workshop speakers reported on a number of innovative techniques that NASA could adopt to improve the rigor of its project management. These included use of probabilistic methods in predicting schedule performance[28], use of analytical techniques to optimize and "right size" project organizations[23,37], and use of project "simulation" to identify sources of project risk that warrant management attention[39]. These techniques were examined in detail by the ODT in tracks 2 and 3 of its research, and are summarized in the post script at the end of this memorandum.

(d) Demonstrate uncompromising ethics. A strong leader must demonstrate uncompromising integrity and ethical standards of behavior in order to build respect team member respect and commitment to achieving the goals of the program. Team members will not follow a leader who they know is capable of unethical behavior and decision making. This behavior on the part of the leader will also foster cynicism within the rank and file of the organization, compromising the ability to achieve the mission.

Principle 4: Facilitate Wide Open Communication.

The fostering of open communication has always been a cornerstone of good project management. This communication can and has been stifled by leaders who have not been interested in hearing bad news or to be bothered with problems. In these instances, the bearer of bad news may avoid trying to communicate problem issues to upper management by shifting the problem to others in the organization, even if they do not have the resources to handle it. Management must foster open and honest communication without retribution. The organization must be open to bad news and be prepared to solve the inevitable problems that always occur. The ODT found evidence of good communication in several programs, particularly in the DoD programs: Virginia Class Submarine, JSF, F-117A, EELV, and ALS/NLS.

Dr. William Starbuck of New York University identified several reasons why organizations suppress communication and have trouble learning from both success and failure.[20] Organizational learning can produce benefits, but many organizations have trouble learning from success. They tend to over-learn successful behaviors and become overconfident. Success rigidifies behaviors and limits awareness of environmental changes. One result is that future failures become inevitable, and when these serious problems develop and

warrant new behaviors, organizations have difficulty *unlearning* what has become ingrained. "Success leads to specialization and exaggeration, to confidence and complacency, to dogma and ritual." On the other side of the fence, organizations also have trouble learning from failure —both small and large. They have strong tendencies to explain away failures as being idiosyncratic and to overlook possible systemic causes. This tendency has been referred to as the "normalization of deviance" by author Diane Vaughn and others in examining the Space Shuttle Challenger accident.[32] Indeed, faulty communication was found by the CAIB to have contributed to the loss of the Space Shuttle Colombia.

> ### *Organization Causes of the STS-107 Failure:*
>
> *The organization causes of this accident are rooted in the Space Shuttle Program's history and culture...Cultural traits and organization practices detrimental to safety were allowed to develop, including: reliance on past success as a substitute for sound engineering practices (such as testing to understand why systems were not performing in accordance with requirements); <u>organization barriers that prevented effective communication of critical safety information and stifled professional differences of opinion</u>; lack of integrated management across program elements; and the evolution of an informal chain of command and decision making processes that operated outside the organization's rules.*

Figure 8. Columbia Accident Investigation Board's finding Regarding Communication Factors (underline emphasis added).

A true leader encourages the rapid reporting of bad news and is prepared to allocate the appropriate resources to solve these issues as they arise. This is possible only if all members of the organization are sure that they can freely discuss any issue, good or bad, and not be punished for being the messenger. Such an open discussion approach can only be fostered by setting an example in meetings and in one-on-one interchanges. All members of the organization must know that management is available and receptive to communication at any time. Closed doors will often lead to closed communications. By literally having an open door and allowing team members to interrupt when communication is required, management will enhance the communications stream that is vital for organizational success. There will, of course, be exceptions to this policy at times, but to keep the lines of communication open, managers would do well to keep the doors open.

Dr. Walter Hammond went a step further in his presentation, noting that the organization needs to create and continuously nurture an "open" corporate culture. Participation enhances understanding, acceptance, and the ability to communicate openly and freely. However, Dr. Hammond warned against arbitrarily bringing people together to force them to communicate. Forced communication could create communication ambiguity, foster the hiding of bad news, and unintentionally discourage the team members from discussing grievances.[21] Furthermore, it was noted that many strong leaders, by nature of their strength, have a presence that could intimidate those who work for them. Leaders should keep this in mind and endeavor to take steps to minimize intimidation so as to avoid the development of a "cult of personality" situation that can completely stifle effective communication.

In today's workplace, electronic media – mainly in the form of email – has become a dominant form of communication. Organizations must face this reality, but must work hard to encourage one-on-one communication. This means that the leaders must leave their offices and actively seek out information; it is much easier to get information by good, interactive conversation than by an interactive electronic exchange. Face to face meetings allow questions and answers to be used to clarify points that would take many emails to accomplish. This is best exemplified by David Packard's "manage by walking around" philosophy: leaving the office and literally walking around and meeting with organization members to discuss the activities in which they are involved.   As an example, the DC-XA program used daily telecons with all the contractors and leaders from the appropriate disciplines to identify issues and allow the team to immediately formulate a plan to resolve them. Near-term schedules were used as a point of reference in all discussions.[14]

Probably the most important principle that an organization can use to ensure open and free flowing communication is to abide by the adage of "praise in public and criticize in private." Public criticism is the surest method of stifling communications. Few individuals will dare to come forward with critical information if it is known that this might bring public criticism. On the other hand, it is not suggested that managers forego criticism that is required, but rather that they deal with it behind closed doors.

Principle 5: Develop a Strong Organization.

The fifth key principle of success is development of a strong organization to execute the project. Dr. Starbuck presented his work on why organizations fail and how organizations change over time. He emphasized that organizations can remain effective over long periods if three interdependent pillars – culture, rewards, and structure – are carefully designed and aligned.[20] This is a key finding of the ODT workshop process because it emphasizes that program managers must expend resources designing and monitoring not only the organization's structure but also its culture and rewards system. These three pillars are discussed in more detail below.

(a) **Culture.** Fundamentally, culture consists of the shared beliefs and behaviors of the individuals in the organization. Elements of culture include, for example, language, ethics, folklore, dress and behavioral norms. Dr. Starbuck emphasized that organizational culture typically takes a long time to create, but can be fragile, thus requiring periodic and thoughtful management attention. Ideally, an organization's culture should foster conflict management and openness to communication, especially for organizations involved in high risk, technologically complex endeavors like NASA. Culture can be influenced using multiple strategies: careful employee selection, on-going training, employee performance monitoring, and rewards. According to Dr. Starbuck, careful employee selection is the most influential strategy among these options.[20]

The ODT identified the NPOESS as an outstanding example of careful organization design and culture management.[24] The NPOESS program intentionally sought to create a new culture unique to their joint program office by co-locating personnel from the three contributing agencies, DoD, National Oceanic and Atmospheric Administration (NOAA), and NASA in a separate facility removed from their agency home offices. They carefully negotiated respective roles and responsibilities and documented them in a tri-agency memorandum of agreement before staffing and initiating integrated program office operations. This included identifying in advance specific positions in the organization that would be filled by each agency. In this way, they carefully removed as many potential organizational conflicts and barriers to success as possible before moving into program execution. In addition, management focused the attention of the integrated multi-agency staff members on the joint organization's unique vision and goals, in an effort to foster the emergence of a new organizational culture.

(b) **Rewards.** Rewards are used to align the behavior of team members with the organization's goals and must reinforce the organization's priorities. For example, to get quality, rewards must depend on quality. To get communication, rewards must depend on communication. Sherman Mullin cited positive organizational culture as one key to the success Lockheed Skunk Works development of the F-117.[11] Management endeavored to foster desired behavior by action, not just by pronouncement. They particularly used a reward system, sometimes one that was outside the normal corporate awards system, to establish a precedent for excellence. In addition, they attempted to allow for honest mistakes and failings among the team members, thus fostering investigation and improvisation on the part of all the team members and allowing for the creation of a learning organization.

Dr. Starbuck emphasized that rewards (and punishments, if also used) are more effective to change behavior the closer they are granted to the observed behavior. NASA, as a government agency, must work within federal regulations to design and implement reward programs. Government civil service regulations limit the availability of financial rewards and reward timing. Thus, program managers may need to find creative alternative ways to reward desired behavior and facilitate culture change.

(c) **Structure.** Organization structure consists of two elements: formal line organization which describes direct reporting management and supervision pathways, and informal communication and integration structures that constitute how individuals in the organization actually work. The latter informal structure in a

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typical large NASA or DoD program consists of a hierarchy of decision making boards informed by technical working groups and integration panels. At the lowest level, the organization structure may consist of a set of integrated product, process or task teams that are established to execute the day to day activities of the project. The challenge in using a "shadow" boards/panels/teams organizational approach is to keep them lean and limited in number. An excessive number of boards, panels and teams can confuse the rank and file staff as to who is responsible for executing, reviewing and approving the technical work products: the program/project/line organizations, or the shadow organization of boards, panels and teams. Boards should rightly be chartered to implement configuration control rather than produce technical work products.

A fundamental principle of organization structure design is to align the organization with the system or product architecture, so that personnel understand clearly what they are responsible for delivering. This principle was well understood by the leaders of the Apollo program. Dr. George E. Mueller, who served as associate administrator for manned space flight at NASA Headquarters during Apollo, emphasized the importance of utilizing a common organization structure at each tier in the program organization.[30] An example of this principle is shown in Figure 9, which illustrates how a common organization structure establishes well defined interfaces, and therefore communication pathways, between the managers of the same functions at each tier in the program organization.
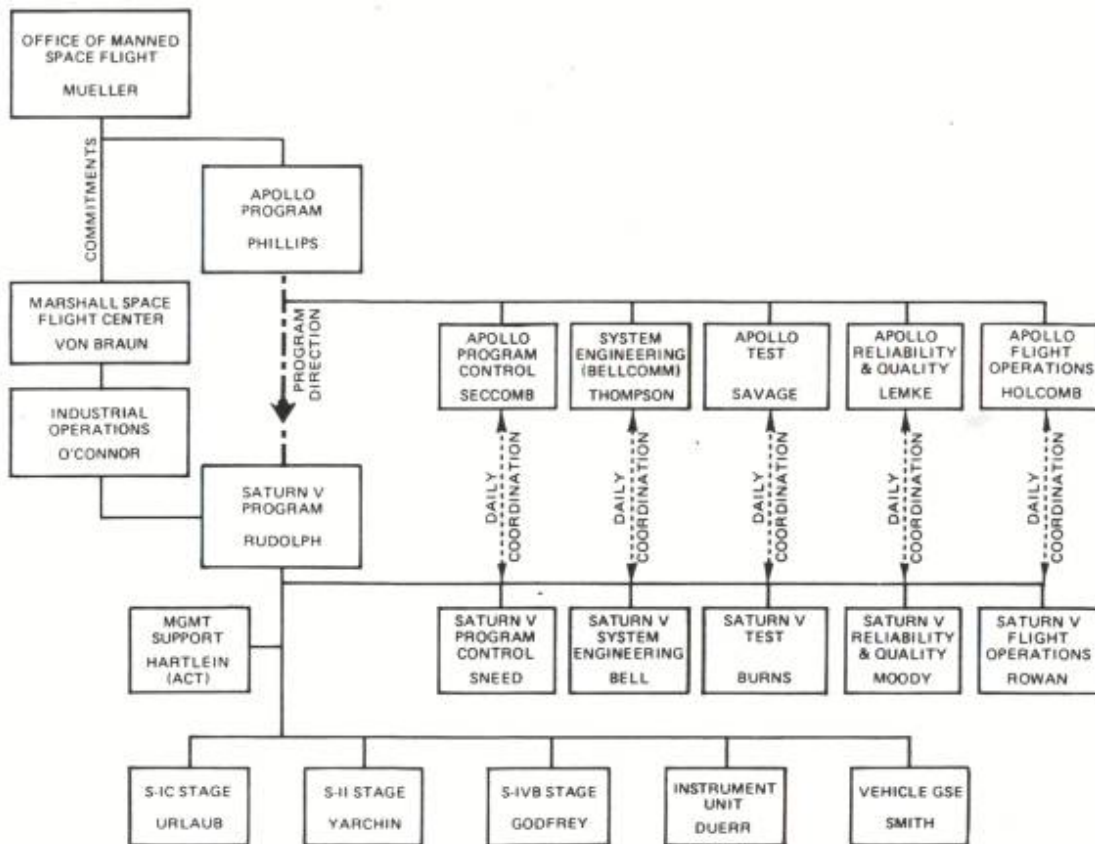

Figure 9. Apollo Organization Structure with Common Units at Each Program Tier. [30]

The Virginia Class Submarine Program, presented by Mr. George Drakeley, deputy program manager, is another case example of the value of a strong organizational architecture that is well aligned with the product being produced. This program's structure and approach is an excellent example of the Integrated Product and Process Development (IPPD) acquisition methodology developed by the DoD in the 1990s to streamline major weapons systems acquisition. In this case, the submarine design and construction teams were organized along three lines (see Figure 10). Major Area Teams (MATs) were established to design and produce each major segment of the submarine (e.g. pressure hull, engine room, etc.). System Integra-

tion Teams (SITs) were established to design and produce those systems which are distributed throughout the submarine (e.g. electrical power, hydraulics, etc.). Process Integration Teams (PITs) were set up to design and implement common processes such as cost, schedule, risk, and configuration management. A single Major Area Integration Team (MAIT) was established to integrate across the MATs, SITs and PITs, essentially performing the SE&I functions via the coordination and integration of the various team activities. Three implementation techniques were critical to making this IPPD structure work: (1) early selection of the design/build contractor team; (2) "badge-less" team membership consisting of active duty military, government civilian, and contractor staff; and (3) cross-team membership with the MAIT drawing its membership from the MAT, SIT and PIT team leaders as appropriate. The payoffs of this IPPD organizational architecture and acquisition approach are well documented in a DoD case study published in 2000.[31] These payoffs included: a shortened overall design cycle/schedule, greatly reduced number of change orders from less problems encountered during construction, considerable cost avoidance in producing the first vehicle, and fielding an operational weapon system that effectively balanced capability and flexibility with cost.
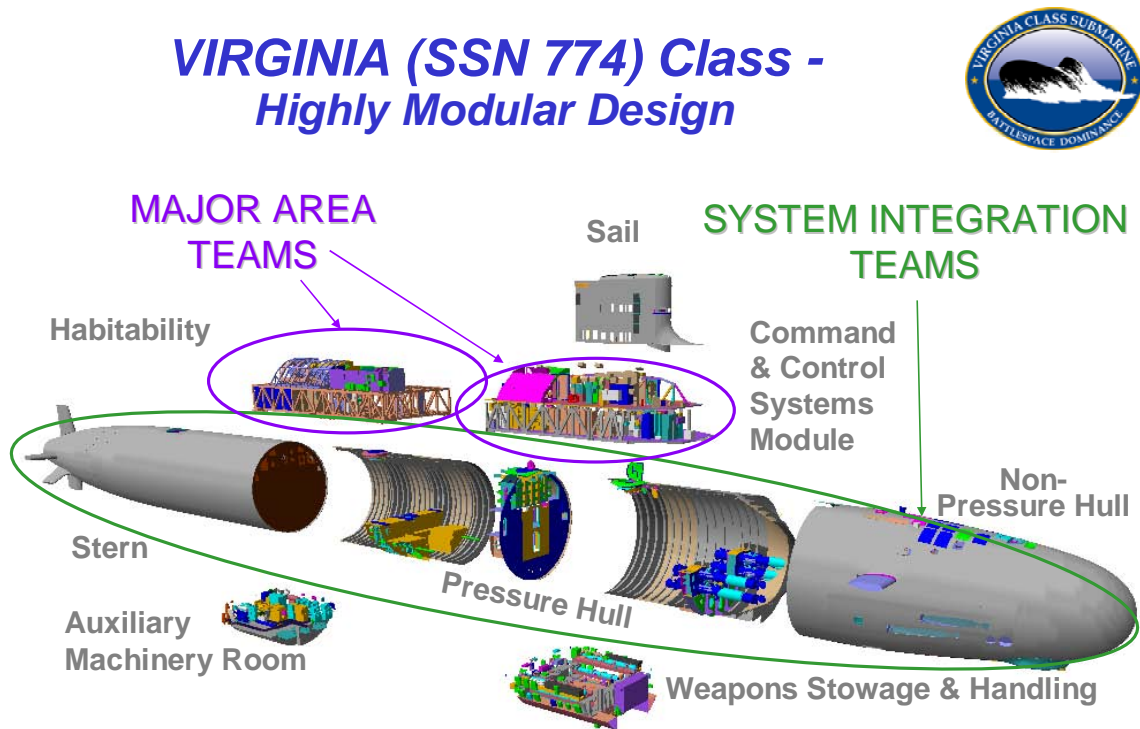

Figure 10. NAVSEA Virginia Class Submarine Organizational Approach Featuring Multi-tiered Integrated Product/Process Teams.[19] [12]

Dr. Starbuck proposed that the most important structural property is communication. Dr. Starbuck emphasized that people talk upward and listen upward, and they avoid telling bosses what the bosses do not want to hear. Thus, managers need to be very sensitive to the signals they put out. In addition, Dr. Starbuck talked about the inevitable and often frequent conflict between engineers and managers. Specifically, he suggested that organization structures should focus on communication channels rather than rules, so that disagreements between managers and engineers are useful, rather than divisive.[20] Well designed organizational architectures clearly establish these natural communication channels through structuring. The Apollo structure shown in Figure 9 accomplishes this by establishing standard common functions at multiple organization tiers. The NAVSEA Virginia Class Submarine Program organization shown in Figure 10 accomplishes this by chartering teams composed of members who need to communicate across their organizational interfaces in order to accomplish effective system integration.

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Another consistent characteristic of successful project organizations was the use of small teams of individuals, at least at the initiation of the programs. Coordination was facilitated, as in the case of the Skunk Works, SpaceX, and X-38, by the entire team being located on the factory floor – or at least in the same facility. Elon Musk specifically emphasized the development of a small team of high-priced and valued individuals, as opposed to the alternative approach of creating a large team of varied-priced individuals that is more characteristic of the broader NASA organization and aerospace contractor base. He has attempted to create a cohesive team where individuals are more broadly involved in the development process, with cross training and multiple functional responsibilities.

The authors believe that NASA works at its very best when it uses small "tiger teams" to tackle high priority, challenging problems. Most new program formulation in the agency occurs first in a 30, 60, or 90 day tiger team study. A prime recent example of this technique was the 60 day Exploration Systems Architecture Study (ESAS).[35] This study was established by NASA Administrator Michael Griffin in May 2005 in order to move the VSE into its next phase of development. A primary product of the ESAS study was the architecture of the Crew Transportation System intended to replace the Space Shuttle, and the acceleration of its planned IOC from 2014 to 2012. The agency's ability to quickly formulate, staff, and execute high priority studies via tiger teams is enabled by the breadth and depth of NASA's staff, their orientation along technical discipline lines, and the informal communication networks that have been built at the working staff level. These discipline-oriented "communities of practice" enable communication between experts within each discipline in spite of the geographic and cultural barriers which separate the ten agency field centers.

Principle 6: Manage Risk.

Managing risk involves employing a continuous and evolving risk-management process that is complemented by an extensive rapid prototyping program using modeling and simulation, testing, and hardware/software-in-the-loop tests.

NASA has always considered the risk of loss of the crew and loss of the mission in its decision-making. In fact, in the early days of Apollo, quantitative goals were established and estimates of both of these risks were required. However, during the later Apollo era and the Shuttle era, NASA relied primarily on qualitative measures to estimate and control mission success and safety risk.[33] Further, NASA addressed technical and developmental risk qualitatively, relying on concepts that had reached a given level of maturity, as measured on a qualitative technology readiness level (TRL) scale, to be included in proposed designs. In a similar fashion, cost and schedule risk (the risk of cost overruns or schedule slippages) were addressed by employing bottoms-up, judgmentally-based approaches not tied directly to the key technical risk drivers that were often the causes of these undesired consequences.

Prior to the Challenger accident, it is fair to say that the primary approach taken by NASA toward risk was qualitative and judgmentally based. The analysis that was performed took the bottoms-up approach previ-
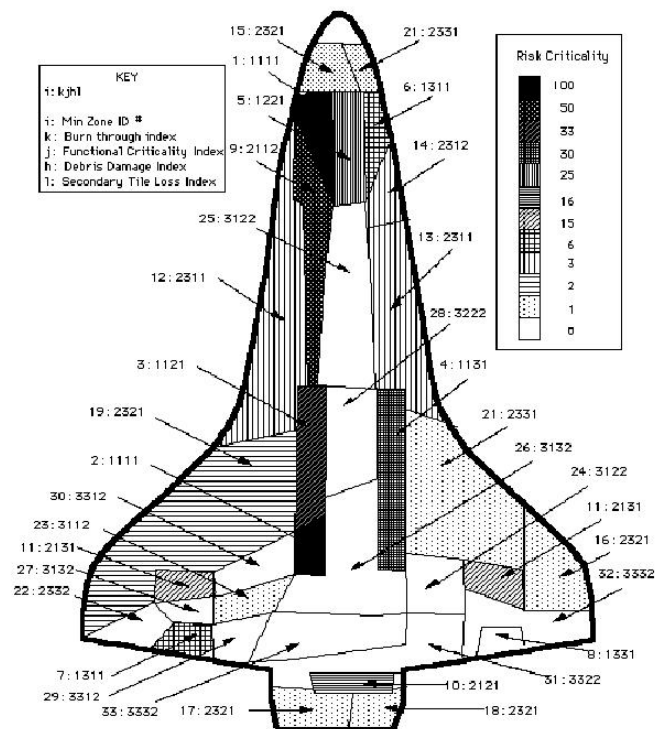

Figure 11. Shuttle Tile Damage Risk Map. [25]

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ously described. This is clearly exemplified by the Failure Modes and Effects Analysis and Critical Items List (FMEA/CIL) undertaken to address safety and mission risk. These analyses proceed from the local, component-related failure issues, to the more global systems and vehicle-related issues using deductive logic rather than the inductive logic more characteristic of top-down analytical approaches. Cost estimation provides another example. When cost estimation was undertaken, it was based either on a bottoms-up actuarial approach or upon mass-driven cost estimating relationships.

The ODT invited Professor Elisabeth Paté-Cornell to present a lecture on her work. She explained that her 1990 study was directed at the problem of the loss of, and damage to, tiles on the belly of the Shuttle Orbiter.[25] Since the data used was based upon post-flight observations of the first 33 flights of the shuttle, it included stack debris, micrometeoroid and Orbiter debris, as well as landing debris, but it did not address debris strikes to the reinforced carbon-carbon used on the leading edges of the shuttle, which was the proximate physical cause of the demise of the Columbia mission. Professor Paté-Cornell's study had used this historical data in combination with design information concerning the placement of critical systems, and the reentry thermal physics information to develop a risk map (see Figure 11) for the shuttle belly tiles and to recommend a continuing inspection program related to these tiles based upon the combined risk "map" that was produced and on the priorities that it displayed.

Subsequent to the Challenger accident, and as a result of the Rogers' Commission Report[34], and particularly due to the efforts of one commission member, the late Professor Richard Feynman, NASA was urged to take a more quantitative approach toward risk. In response to these recommendations, NASA established three pilot studies to employ quantitative risk assessment using the scenario-based probabilistic risk assessment approach pioneered in the 1970s by Professor Norman Rasmussen in the commercial nuclear industry. These three studies addressed the safety and mission success risk of the main propulsion pressurization subsystem (performed by Lockheed Palo Alto), the auxiliary power unit (APU) (performed by a McDonnell Douglas-Pickhard Lowe and Garrick team), and the thermal protection system (TPS) (performed by a Stanford-Carnegie Mellon team). This latter study was led by Professor Elisabeth Paté-Cornell of Stanford University.

Professor Paté-Cornell indicated that one of the most important lessons learned from her work on the Space Shuttle and elsewhere was the importance of collecting operational data on an ongoing basis, and embedding it into a risk-based structure to provide an ongoing or "living" measure of the residual risk of continued operation. She cited the crash of the Concorde on July 25, 2000 as another example of how this data might have been used to forestall failure. Her records research indicated that during the 75,000 hours of previous Concorde operation, 57 tires had burst, and several times, debris had come close to penetrating the fuel tank before the crash in 2000. The Professor pointed out that the use of such a "living accident precursor" system had been shown to be of value in such diverse areas as hospital anesthesia, the Ford/Firestone Explorer tire failure, and the leading edge of the Boeing 737.

Professor Paté-Cornell's presentation, combined with the ODT's own study and presentations of the information contained in the report of the CAIB, indicated the value of managing safety and mission success risk on a continuing basis using quantitative models of potential accident scenarios, combined with developed operational data, and physical models of relevant phenomena.[25]

Figure 12. Lockheed Martin X-35 JSF Concept in Flight.

The JSF Program presentation indicated the value of the continual use of modeling and simulation tools to track and "buy down" the risk of development early on and with rapid prototyping of design concepts later.[26] Combining these phenomenological simulation tools and prototyping with the logical simulation tools provided by quantitative risk assessment may provide a better way to assess, monitor, and track developmental risk and marshal the scarce test resources available in the NASA constrained budgetary and low production run environment.

The X-38 project[15] recommended picking the "top 10" risks and focusing on those with the greatest payoff. The program then used these identified risks to guide the "build a little, test a little and grow a little" philosophy employed throughout vehicle development to effectively manage the project's risk. The primary focus of the X-38 philosophy was "you can't do too much modeling and simulation." However, the program recognized that it needed actual data to anchor these model results. Guidelines driving the X-38 modeling and simulation were: 1) don't extrapolate beyond known physics and test assumptions; 2) add complexity only as understanding increases, and 3) expect and plan to make modeling and simulation an iterative process. The X-38 project also believed in the power of frequent integration tests (these can be defining moments for a project) to reduce risk. Integration tests push for opportunities to bring things together for early integration and validation and assess how integration is going, without waiting to the end of the project.

Risk management is critical in the success of all programs—not just manned missions. This insight was reinforced by the example of the EELV program presented by Major Andrew Chang from the USAF EELV Program Office.[27] After a review of the performance history of their ELVs in the early 1990s, the USAF determined that their experience with launch failures was worse than that of NASA. As a result, in advance of beginning development of new EELVs (Atlas V and Delta IV), decisions were made to:

- Concentrate their space resources under a unified command;
- Establish an independent readiness review team similar to NASA's flight readiness reviews; and
- Establish an independent risk management council and a single government mission director for each individual mission.

As of 2005, eight flights — five on Atlas V and three on Delta IV — have all been successful. However, this achievement was accomplished with the application of considerably increased government resources. The program originally started with 150 full time equivalent (FTE) staff, and by FY04 workforce had increased to 350–400. This lesson learned stands in stark contrast to the "lean" staffing approach and systems development philosophy which Adm Craig Steidle (ret.) brought to the startup of ESMD in 2004.

Principle 7: Implement Effective Systems Engineering and Integration.

The final key principle, Implement Effective Systems Engineering and Integration, is composed of several sub-principles:

> (a) Develop clear, stable objectives and requirements from the outset;
> (b) Establish clear and clean system interfaces;
> (c) Maintain effective configuration control;
> (d) Use modern information technology and analytical tools to model and simulate system performance, including organizational performance, well in advance of hardware development.

Aerospace programs are typically developmental in nature. Sometimes they are revolutionary in scope. The very nature of developmental programs implies that the outcome is, at least to some degree, uncertain. In such programs, shifts in objectives result in a corresponding growth in requirements. These shifts and the resulting requirements growth lead to program delays, cost increases, and even to program failure or cancellation. In successful programs, the traditional role of systems engineering and integration (SE&I) has been to stabilize the development process and to keep the program under control. A successful SE&I effort is characterized by the initial establishment of a clear and stable set of objectives for the program at the outset, and the careful and thoughtful development of a minimal set of requirements for the achievement of those objectives.

(a) **Develop clear, stable objectives and requirements from the outset**. Good systems engineering starts with good requirements and good management practices that will result in clear, stable program objectives. The managers of all the programs presented at Workshop VI (see appendix F) stressed the need to develop clear, stable requirements from the outset and to take the necessary time on the front end of the program to

develop, stabilize, and build consensus. Several programs (F-117A JSF, SpaceX, X-38) proposed that top-level program requirements be limited to one page, and all agreed that the focus should be on achieving key driving requirements. The F-117A program[11] had five requirements: (1) To provide program security, (2) To meet low observable specification (Stealth); (3) To have precision guided weapons capability; (4) To deliver a 5000 pound payload; and (5) To achieve initial operations capability (IOC) by the specified target date.

The JSF program developed and employed a strategy-to-task-to-technology approach to prioritize needed technologies. Based on the Operational Requirements Document (ORD) and concept of operations (CONOPS) model, the program defined operational capabilities and had designers, operators, and technologists work together to identify and prioritize mission-enabling technologies. The program invested billions into the resulting technologies. Not all technologies required a huge investment, but some did require a change in philosophy. The example, discussed by Mr. Paul Wiedenhaefer, JSF Requirements Lead, was Avionics Open Architecture and supporting technologies to address affordability.[26]

John Muratore, the X-38 program manager[15] recommended against writing documents or specs just to fill in the squares (volumes get shelved that no one will ever read or use) and recommended careful control and tracking of interfaces. "Your strengths can also be your weaknesses." He summarized that requirements traceability can be a good value, but it can also be a program's downfall. Traceability itself is not the goal; the key is to employ a traceability tool that will improve the product or the process.

Successful programs, such as Apollo and JSF demonstrate that it takes considerable initial effort and time to develop the set of key driving requirements, but that this significant effort more than pays for itself during the course of later program development. Paul Wiedenhaefer related that the JSF ORD took over five years to develop while rapid system prototyping (i.e. fly-offs) was occurring. The Program Office also developed, maintained, and matured a CONOPS Model to evaluate contractor developed architectures and spent significant effort in achieving consensus around the cost models to reduce future challenges of cost analysis and modeling results.

(b) **Establish clear and clean system interfaces**. SE&I performs a critical role early in the design effort in the establishment of interfaces between the discrete elements in a properly defined system and the hardware and software being developed to implement the design requirements. The SE&I team must clearly delineate boundaries between subsystems, document them in a concise interface control document, and continually monitor design team compliance with these documents throughout the design process.

In addition to the need for clean product/system interfaces, many presentations throughout the workshops emphasized the importance of establishing clear and clean organization interfaces. This includes documenting responsibilities, authorities and accountability of the organizational units on each side of the interface so as to drive out a common understanding and operating agreement. Specifically, they emphasized the benefits derived from designing the program organization structure to mirror the system architecture, with particular emphasis on the areas of the design that were nontraditional or developmental. Skunk Works Program Manager Sherman Mullin reiterated this point several times in his presentation.[11] Program experience relative to other NASA and other government programs identified the importance of allowing the contractor the freedom of structuring its organization to keep the interfaces clean and the accountability clear. In particular, government-enforced contractor teaming was to be avoided because it tended to obscure the lines of authority and to complicate the structure of the program organization. An interesting contrast to this view was seen in the Virginia Class Submarine Program, which implemented a congressionally directed teaming arrangement between Northrop Grumman Newport News Shipbuilding and Electric Boat as the joint design/build prime contractor for this next generation submarine. The Virginia Class program mitigated the potential organizational and system interface complexity that could have resulted from this teaming via the IPPD structure described under Principle 5 above. Virginia Class deputy program manager George Drakely emphasized three implementation techniques that aided in mitigating this teaming risk: (1) forming "badgeless" integrated government/contractor MAT/SIT/PIT membership, (2) establishing crisp program content responsibilities for each contractor , and (3) forging an agreement to split all profit evenly between the two contractors.

(c) **Maintain effective configuration control**. Once top level objectives have been agreed to and sold to the program's protectors and customers, once these objectives have been decomposed into a set of system requirements, and once the program organization has established clear, clean interfaces both for itself and for the conceptual system design, then this programmatic "baseline" configuration must be carefully controlled. Several presenters emphasized the need for establishing an early program baseline, consisting of requirements, system concept, budgets, schedules, and risks, then rigorously controlling that baseline as the program moves forward through its lifecycle. The SE&I effort must keep the design team on track, focusing on the key design requirements and being continually vigilant against "requirements creep". Shifting requirements ultimately led to the demise of the National Aerospace Plane program, which started in 1984 as a single stage to orbit technology demonstrator but which ended as a collection of various hypersonic technology development activities at its termination in 1993. [36] An uncontrolled budgetary estimate contributed to the failure of the Space Exploration Initiative under the first Bush presidential administration.

(d) **Use modern information technology and analytical tools to model and simulate system performance well in advance of hardware development**. In the past, the SE&I effort was very labor intensive. System engineers were required to develop a peer level understanding of each of the developing designs within each area of the work breakdown structure (WBS) and review these designs against each other. The design reviews were lengthy, comprehensive, effective, but expensive. Recent advances in software (e.g. engineering analysis tools), hardware (e.g. computing platforms), and information processing (e.g. the Internet) have revolutionized the engineering design process. Presently, it is possible to construct computational simulations of system designs to enable many alternatives to be examined during trade studies. Additionally, the use of web-based information management tools can now allow the geographically distributed members of the design team to have access not only to the drawings and specifications of the key design alternatives as they develop, but also to the results of supporting test and simulation data.

There were many programs presented at Workshop VI (JSF, X-38, SpaceX, see Appendix F) that identified simulation based acquisition (SBA) as critical to a program's success. Two outstanding examples of SBA surveyed by the ODT came from the Navy: the Joint Strike Fighter program and the Virginia-Class Submarine program. The JSF program invested upwards of $1B implementing SBA to allow thorough requirements-cost tradeoffs, technology assessment, and virtual system design prior to initiating hardware production.[26] The Virginia-Class Submarine program utilized a single electronic database to integrate all aspects of design, planning, and construction. The database was used to link design with production and business operations, providing a fully integrated electronic data set throughout the lifecycle of the program.[19] In addition, the effectiveness of early developmental hardware/software-in-the-loop testing was enhanced by the existence of this common electronic database.

Postscript – Tracks 2, 3 and 4

This report documents the ODT's first track of inquiry. Three additional tracks of inquiry were subsequently undertaken by the ODT. Track 2 focused on identifying tools, methods and databases that could be used by NASA to design, model, simulate, and assess future program, project, and line organizations. In Track 3, the ODT applied the the most promising tools and methods identified in Track 2 to a series of pilot studies to assess their usefulness to future NASA programs and projects, with a particular focus on emerging organizations involved in implementing the VSE. Track 4 has focused on development of a "toolkit" to capture the results of the first three tracks in a web-served software application for adoption by a broder set of users in the agency. The key findings of Tracks 2 - 4 are synopsized below.

The ODT collaborated with Dr. Starbuck and his staff at NYU to participate in a National Science Foundation sponsored Workshop on Organization Design.[22] Presentations at this workshop provided insight into the current state of the art of Program/Organization Modeling & Simulation (POMS). The premise of POMS is as follows: Program managers need to organize human discipline experts into high performance groups, typically separated by geographic, line organization, program organization, or technical discipline boundaries to meet the unique technical, schedule, budgetary, and other requirements of a program. Thus, the ability to more effectively design, model, and analyze the human interactions typical of complex

program organizations might well prove to be an enabling discipline to future successful program execution.[29]

As a result of the NYU workshop, presentations at the ODT workshops, and research performed under ODT sponsorship, five key POMS tools have been identified and demonstrated in pilot studies by the ODT to date. These are:

1. Historical Program/Project Database. The ODT compiled a database of over 40 historical programs and projects for the purpose of establishing Manpower Estimating Relationships which correlate peak year workforce levels to total program funding, as well as historical program life cycle phase durations which can be used to feed stochastic assessments of schedule risk for future programs and projects.[28]

2. OrgCon®. OrgCon is an expert system desktop software tool which incorporates 350 rules derived from the multi-contingency organization theory. OrgCon is used to examine the alignment or "fitness" of an organization design's internal structure to its culture, constraints and external environment. It can also be used to perform sensitivity studies to optimize the organization design by minimizing "misfits" amongst the 14 fitness factors that OrgCon uses to characterize an organization. The ODT has applied OrgCon to the design of the Constellation Systems Analysis Integrated Discipline Team (IDT) [39]

3. Design Structure Matrix. The Design Structure Matrix (DSM) was developed by the Massachusetts Institute of Technology to solve the problem of graphical representation of project task flows where tasks may be iterative or require feedback. For application to organization design, it can be used to quantify the interdependence and/or information / product flows between organizational units. Dr. Tim Brady of NASA JSC used the DSM technique to analyze the risks that contributed to the failure of the Mars Climate Orbiter and Mars Polar Lander in 1999.[23] The ODT subsequently applied the DSM to successfully design a set of fourteen IDTs used by ESMD Constellation Systems to organize over 200 FTE across all ten NASA field centers for executing the FY05 program.[37]

4. SimVision®. SimVision is a discrete event simulation tool based on information-processing theories. It uses an "agent" based modeling architecture to simulate workers (agents) performing tasks. SimVision was originally developed at Stanford University and has over 15 years of verification and validation heritage. The tool can then be used to right-size organizations, balance workforce assignments, and estimate multiple measures of organization and schedule risk for use in optimizing the final organization design. The ODT has used SimVision in multiple studies to design and simulate project team organizations, products, tasks, and schedules.[39]

5. NASA Project Manager's Toolkit. In FY05, the ODT initiated development of the Project Manager's Toolkit, a web-served software application intended to capture the knowledge developed by the ODT since FY03, and provide the working program/project manager and system engineer/analyst with desktop access to these tools and techniques.[40]

In summary, the ODT has identified and demonstrated several organization design and analysis techniques that, if used in combination with the seven key principles of program success, can significantly improve the agency's ability to field more effective program, project and line organizations for the future.

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14. Dumbacher, Dan, "DC-XA Lessons Learned Discussions." (See Appendix F.5.)
15. Muratore, John, "X38 Program System Engineering Lessons. " (See Appendix F.4.)
16. Branscome, Darrell, "Advanced Launch System."   (See Appendix C.5.)
17. Christensen, Dave, "Space Program Lessons Learned/Best Practices." (See Appendix C.2.)
18. Dankhoff, Walt, "NOVA, Super Saturn Program." (See Appendix F.3.)
19. Drakeley, George, "Virginia (SSN 774) Class Submarine Program." (See Appendix F.10.)
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21. Hammond, Walter, "Optimizing and Synergizing Organizations." (See Appendix A.5.)
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23. Brady, Timothy K., "Framework for Evaluating Architecture, Technology and Organization Options." (See Appendix A.2.)
24. Schneider, Stanley, "National Polar-orbiting Operational Environmental Satellite System (NPOESS) Integrated Program Office." (See Appendix C.4)
25. Paté-Cornell, Elisabeth, "On Signals, Response and Risk Mitigation: A Probabilistic Approach to Precursors Detection and Analysis. " (See Appendix A.4.)
26. Wiedenhaefer, Paul, "JSF, The Affordable Solution, Requirements Definition Process & Lessons Learned."   (See Apendix H.1.)
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Appendices A-H [on companion CD]

Appendix A. Workshop I: Tools and Methods for Organization Design & Analysis. NASA Langley Research Center, August 2003.

A.1   Freddie Douglas, NASA Stennis Space Center, "Lean Principles Implementation in the Program Preparation Phase."

A.2   Tim Brady, NASA Johnson Space Center, "Framework for Evaluating Architecture, Technology and Organization Options."

A.3   Dr. William Starbuck, Stern School of Business, New York University, "Keeping Organizations Effective Over The Long Run."

A.4   Dr. Elisabeth Paté-Cornell, Management Science and Engineering, Stanford University, "On Signals, Response and Risk Mitigation: A Probabilistic Approach to Precursors' Detection and Analysis."

A.5   Dr. Walter Hammond, Jacobs Engineering/Sverdrup, "Optimizing and Synergizing Organizations."

Appendix B. Workshop II: Advanced Mission Operations and Analysis. NASA Johson Space Center, October 2003.

B.1   Barbara Stone-Towns, "NASA/Air Force Cost Model (NAFCOM 2002) Overview, NAFCOM and Organization Structure."

B.2   John D. (Doug) Rask, "MOD Advanced Operations Cadre (AOC)."

B.3   Howard Hu, Jeremy Hart, Ryan Proud and Timothy Straube, "Spacecraft Mission Assessment and Replanning Tool (SMART): A Real-time, Intelligent Autonomous Flight Management (AFM) System for Increased Safety and Performance of Spaceflight Vehicles "

B.4   John D. (Doug) Rask, "Potential Impacts of Automation Technologies on Mission Operations."

B.5   Bebe Ly, Lui Wang, "Autonomous System Architecture."

B.6   Mike Evans, "Overview of Flight Design Templates for Crewed Space Flight."

B.7   John D. (Doug) Rask and Marty Linde, "Flyback Booster Issues."

B.8   Mike Evans and John D. (Doug) Rask, "SLI/CART Trajectory Scenarios."

B.9   Phil Varghese, "On the Road to Autonomous Space Missions, Deep Space 1 Experience."

Appendix C. Workshop III: Organization Design and Best Practices. Williamsburg, VA, Decemeber 2003.

C.1   Dr. John Sterman, "Learning and Process Improvement in Complex Organizations."

C.2   Dave Christensen, "Space Program Lessons Learned/Best Practices."

C.3   Dr. Richard Beck, "Assessment of Intergency Program Management Approaches."

C.4   Stanley Schneider, "National Polar-orbiting Operational Environmental Satellite System (NPOESS) Integrated Program Office."

C.5   Darrell Branscome, "Advanced Launch System."

C.6   Russell Turner, "Contractor Perspective on the Space Flight Operations Contract (SFOC)." Recorded presentation from the CAIB testimony June 12, 2003.

C.7   Richard H. Buenneke, "On Not Confusing Ourselves: Insights on Organization, Policy and Culture from the Columbia Accident Investigation."

C.8   Ming Tang, "National Aerospace Plane Organization and Management."

C.9   Carey M. McCleskey, "STS Root Cause Analysis Organization Insight."

Appendix D. Workshop IV: Layout of the Next Program Organization Structure. NASA Stennis Space Flight Center, February 2004.

D.1   Howard Cotterman, John Chiorini, "Technology Management Strategy and Project Cycle."

D.2   Dr. Richard Chick, "Program Management Best Practice Overview."

Appendix E. Workshop V: Layout of the JSF-Like Program Structure. NASA Langley Research Center, March 2004.

E.1   Jim Whalen, "Development Methods/Strategies and the Project Cycle, DOD 5000.1 & 2, NASA 7120.5B, and Visual PM Comparison."

Appendix F: Workshop VI: Building a Historical Program Database. NASA Johnson Space Cneter, May 2004.

F.1   Gwynne Shotwell, "SpaceX Overview."

F.2   Dr. Aaron Cohen, "Comments about the Apollo Program."

F.3   Walt Dankhoff, "NOVA, Super Saturn Program."
F.4   John F. Muratore, "X38 Program System Engineering Lessons."
F.5   Dan Dumbacher, "DC-XA Lessons Learned Discussions"
F.6   Major Andrew Chang, "EELV SPO Overview"
F.7   Greg Allison, "Kistler, HyTEx, PARSEC and Sundry Approaches to Project Management."
F.8   Dr. Roger Launius, "Reflections on Project Apollo."
F.9   Sherman N. Mullin, "Lockheed Skunk Works Program Management with Focus on the F-117 Stealth Fighter Program"
F.10   George M. Drakeley III, "Virginia (SSN 774) Class Submarine Program."
F.11   Jim Snoddy, "Defining and Applying Insight."
F.12   Greg Smith, "Schedule Risk Algorithm Development"

Appendix G: Workshop VII: Writing the Report. NASA Langley Research Center, August 2004.
G.1   None.

Appendix H: Special Web Presentations.
H.1   Paul Wiedenhaefer, "JSF, The Affordable Solution, Requirements Definition Process & Lessons Learned." Pre-Workshop VI Presentation on May 13, 2004.
H.2   Dr. George Mueller, "Apollo: First Space System of Systems," presented to NASA Exploration Systems SE&I Benchmarking Workshop, Pasadena, California, December 2004.
H.3   Vincent J. Bilardo Jr, Program/Organization Modeling & Simulation (POMS) Initiative, June 13, 2005.

Appendix I: ODT Membership and Workshops

Table I-1. Members of the Organization Design Team.

Name	Organization	Title
Vincent J. Bilardo, Jr.	NASA Glenn Research Center	Co-lead of Organization Design Team, GRC Crew Launch Vehicle Project Office
Dr. John J. Korte	NASA Langley Research Center	Co-lead of Organization Design Team.
Dallas Bienhoff	The Boeing Company	Chief Architect, Space Exploration Systems
Darrell R. Branscome	SAIC Hampton, Virginia	Senior Systems Engineer
David Cheuvront	NASA Johnson Space Center	Senior Systems Engineer, Exploration Systems Engineering Office
Dr. Robert L. Chick	The Boeing Company	Lead, Boeing Best Practices
Walter Dankhoff	SAIC/Space Propulsion Synergy Team	Chairman, also Retired NASA HQ
Freddie Douglas, III	NASA Stennis Space Flight Center	Head, Systems Management Office
Dale Dugal	Hernandez Engineering Incorporated	Senior Product Assurance Engineer, NASA MSFC
Joseph R. Fragola	SAIC New York	Principle Scientist
Thomas J. Gormley	Gormley & Associates	President
Dr. Walter E. Hammond	Jacobs Engineering, Sverdrup	Senior Systems Engineer, Support NASA MSFC
James J. Hollopeter	Earth Space Applications	President
Kevin J. Langan	SAIC	Senior Systems Engineer
Albert E. Motley, III	NASA Langley Research Center	Senior Systems Engineer, Systems Management Office

Deborah J. Neubek	NASA Johnson Space Center	Deputy Manager, Advanced Design Office
Mark Prill	NASA Marshall Space Flight Center	Head, Technology Requirements Planning
Randy Sweet	Lockheed Martin Corporation	NGLT Deputy Program Manager
Dr. Alan Wilhite	National Institute of Aerospace	Langley Distinguished Professor
Keith L. Woodman	NASA Langley Research Center	Systems Engineer, Space Access & Exploration Program Office

Table I-2. Organization Design Team Workshop Summary.

Workshop	Location, Date	Title	Highlights
I	LaRC, August 2003	Tools and Methods for Organization Design & Analysis	Five invited talks. Dependency Structure Matrix (DSM) tool for evaluating organizations
II	JSC, October 2003	Advanced Mission Operations and Analysis	Five invited talks focused on autonomous space flight as means of reducing organization costs.
III	Williamsburg, VA. Decemenber 2003	Organizational Design and Best Practices	Eight invited talks focused on program/organization design.
IV	SSC, February 2004	Layout of the Next Program Organization Structure	Prototyping an organization design process.
V	LaRC, March 2004	Layout of the JSF-Like Program Structure	Project life-cycle definition and FTE estimation process.
VI	JSC, May 2004	Building a Historical Program Database	Twelve invited talks focusing on program best practices and lessons learned.
VII	New York University, June 2004	Conference on Organization Design, co-sponsored by NYU Stern School and National Science Foundation	Key org design tools (OrgCon, SimVision) identified for application in pilot studies.
VIII	LaRC, August 2004	Analyzing the Results and Writing the Final Report	Synthesis of Seven Key Principles.